Energy Conversion and Management 199 (2019) 111892

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Aging based design and operation optimization of organic rankine cycle systems

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ARTICLE INFO

Keywords:
Organic rankine cycle
Working fluid selection
Decomposition rate
Aging model
Optimal operation scheduling

ABSTRACT

The Organic Rankine Cycle (ORC) is a power generation cycle similar to the conventional Rankine cycle which runs on a working fluid other than water. The selection of a working fluid is a critical part of designing an ORC system. Researchers have selected working fluids based on various performance criteria including thermal efficiency, safety, output power, and investment cost. It should be noted that working fluids are degraded over system operating lifetime, and this will affect the system performance. As a result, working fluid should be selected considering fluid degradation mechanism in long-term operation that is studied in this paper.

The objective of this work is to develop a model which optimizes simultaneously the working fluid selection and operation schedule of ORC systems. Firstly, an aging based model of the ORC system is proposed which selects the optimal working fluid considering fluid decomposition over time. Then, an aging based optimization model is developed optimizing operating schedule of the system. The model is applied to a combined gas turbine-ORC system which toluene and cyclopentane are compared as two working fluids. The results revealed that by utilizing the toluene as a working fluid, the degradation rate and cost of electricity generation and maintenance is much higher (about 30%) and using cyclopentane will be more economical during the system lifetime. Finally, this study indicates that selection of working fluid just on the basis of the start point power production is not reliable and the design and optimization of the ORC systems should be evaluated through the long-term operation.

1. Introduction

Organic Rankine cycle (ORC) is a promising way for low-grade waste heat (such as solar energy, geothermal energy, and biomass energy) utilization [1].

The performance of an ORC system is strongly related to the working fluid and operating conditions of the system. Working fluid selection is a primary task in customizing an ORC to a specific background process for waste heat recovery. The working fluids are selected based on available waste heat characteristic and application criteria. The main ranking criteria of working fluid selection are system efficiency, investment cost [2], thermodynamic, environmental and safety standards [3].

Moreover, defining the operational conditions of the ORC that achieve the maximum utilization of waste heat is important. There are a number of studies on the ORC systems, most of which focus on thermodynamic analysis and efficiency improvement using different working fluids. Carcasci et al. [4] presented a comparison between four different working fluids in order to find the best choice. The toluene, benzene, cyclopentane, and cyclohexane were selected and the design was performed by means of a sensitivity analysis of the main process parameters. The optimization was done by varying the main pressure of the fluid at different temperatures of the oil circuit. The results revealed that toluene, benzene, and cyclohexane operate best without the superheater, while cyclopentane operates best with the superheater, although its performance was the worst. Thermodynamic analysis of an organic Rankine cycle integrated with an intercooled gas turbine using four different organic fluids was carried out by Winchler et al. [5]. Two different plant configurations were studied, in which the waste heat was recovered from the exhaust gas or from the intercooler. Finally, a cycle analysis by varying the expander inlet pressure was presented.

Zhang et al. [6] designed a regenerative organic Rankine cycle

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https://doi.org/10.1016/j.enconman.2019.111892
Received 19 May 2019; Received in revised form 29 July 2019; Accepted 30 July 2019

system to recover the exhaust heat of a diesel engine and the influence of the intermediate on performance parameters was analyzed. A performance analysis of the ORC system using the two different working fluids was conducted. The results showed that the zeotropic mixture isopentane/R245fa performed better. Oyewunmi et al. [7] investigated the effects of using working-fluid mixtures in ORC systems operating in combined heat and power (CHP) mode. It was shown that utilizing the working-fluid mixture of n-octane and n-pentane results in an ORC-CHP system with the highest ORC exergy efficiency. Song et al. [8] proposed a one-dimensional analysis method for the ORC systems. Based on the presented method, an ORC system for the industrial waste heat recovery was designed and analyzed. Several researchers have done further studies on the energetic optimization [9,10], exergetic analysis [11,12] and performance evaluation of the ORC combined systems [13–14].

On the other hand, system components degrade over the operating lifetime [15]. The degradation mechanisms affect system physical and chemical characteristics and as a result, system performance deteriorates [16]. Therefore, degradation mechanism consequences should be considered in the optimization procedure of working fluid selection and operation scheduling. Working fluid decomposition is studied in [17,18]. However, the effects of this decomposition on working fluid selection and operation scheduling is not studied.

In this study, optimal working fluid is selected considering the decomposition phenomena. The major novelties of this study are as follows:

- The main novelty of the proposed model is the consideration of working fluid decomposition effects in the design and optimization of the ORC systems. The working fluid decomposition can result in performance deterioration and an additional cost of working fluid makeup. Considering working fluid decomposition effects in the ORC fluid selection leads to the applicable and practical result.
- The rate of working fluid decomposition depends on many factors including operating conditions. Effective management of decomposition rate is a key element of the efficient and reliable operation of ORC system. The proposed model manages decomposition rate by optimizing system's operating schedule.
- Degradation rate and performance of two working fluids (toluene and cyclopentane) are evaluated. Also, the electricity generation and maintenance cost for both of them are compared.

The paper is organized as follows: A brief overview of the problem under study is introduced in Section 2. The modeling and formulation of the system are presented in Section 3. In Section 4, the results of the case study are discussed, and finally, conclusions and contributions are drawn in Section 5.

2. Generic problem statement

Organic Rankine Cycle (ORC) systems are a solution for power production from low to medium temperature heat sources in the range of 80–350 °C. The working principle of an ORC power plant is similar to the most widely used process for power generation, the Clausius Rankine Cycle. The main difference is the use of organic substances instead of water or steam as working fluid. The organic working fluid has a lower boiling point and a higher vapor pressure than water and is thus able to use low-temperature heat sources to produce electricity [19]. There are some main points that should be considered in selection of working fluids.

The first and foremost is working fluid should be nonflammable, for knowing this properties would refer to the auto-ignition temperature, and this is non-fiction, if auto-ignition temperature of a working fluid is high, this working fluid is closed to non-flammable. In addition, boiling point of working fluid determine the type of the heat source. The temperature of heat source should be higher than working fluid boiling temperature. Lower boiling point can lead to a wider range of heat sources including heat recovery process. As a result, working fluids with low boiling point can be used in ORC supplied with low temperature heat recovery system. Another point which causes to select a suitable working fluid for this thermodynamic cycle is volatility because when do not use turbo-expander in a hermetic and tightness container, the range of volatility of working fluid would be low for increasing the efficiency of ORC cycle.

ORC can be combined with a gas turbine (GT) through a diathermic oil circuit in order to convert gas turbine waste heat into electrical power. The combined GT-ORC cycle systems offer high thermal efficiency, economic competitiveness, and environmental advantages.

It also eliminates the need for large heat exchangers to produce steam for electricity generation, because of the ORC working fluids high thermal capacity. The working fluids of an ORC system are chosen to best fit the heat source according to their differing thermodynamic properties, thus obtaining higher efficiencies. Performance analysis of different working fluids in ORCs have been analyzed in [20], and working fluids are prioritized on the basis of their thermal efficiency, output power, investment cost, exergy efficiency, etc. In long-term operation, the choice of working fluid is critical since the fluid must have not only thermophysical properties that match the application but also adequate chemical stability at the desired working temperature. Recently, several studies have been conducted that show the decomposition rate of working fluids at different temperature ranges [21,22]. It is worth mentioning that working fluid decomposition affect ORC system performance. Therefore, the decomposition rate of fluid should be considered in performance analysis and working fluid selection. This study presents an aging based model for ORC systems that considers working fluid decomposition in the modeling and optimization procedure.

3. Aging based optimization model

3.1. ORC thermodynamic model

The ORC system consists of an evaporator driven by waste heat, an expander, a water-cooled condenser, and a working fluid pump which are illustrated in Fig. 1.

The waste heat is recovered in a heat exchanger in the evaporator section. The recovered heat rate from exhaust flue gas is calculated as Eq. (1), [23].

$$\dot{Q} = \eta_{hx} \times \dot{m}_{gas} \times C_{P,gas} \times \Delta T_{gas} \quad (1)$$

In this isobaric process, the evaporator heats the working fluid at the pump outlet to the supercritical condition.

$$\dot{Q} = \dot{m}_{wf} \times (h_2 - h_1) \quad (2)$$

The superheated working fluid passes through an expander in order to generate the mechanical power. In an ideal condition, this process is isentropic, and the expander power can be calculated as Eq. (3), [23].

$$W_{ex} = \dot{m}_{wf} \times (h_2 - h_3) \quad (3)$$

The recuperator recovers heat from exhaust gas of expander to preheat the working fluid. The recovered heat can be calculated as Eq. (4).

$$Q_{rec} = \eta_{rec} \times (h_3 - h_4) \quad (4)$$

The exhaust working fluid after passing through recuperator led to a condenser where it is condensed by a cooling media. The process in the condenser is assumed to be isobaric, and the condenser heat rate can be expressed as Eq. (5), [23].

$$\dot{Q}_c = \dot{m}_{wf} \times (h_4 - h_5) \quad (5)$$

The pressure of the condensate working fluid is increased through

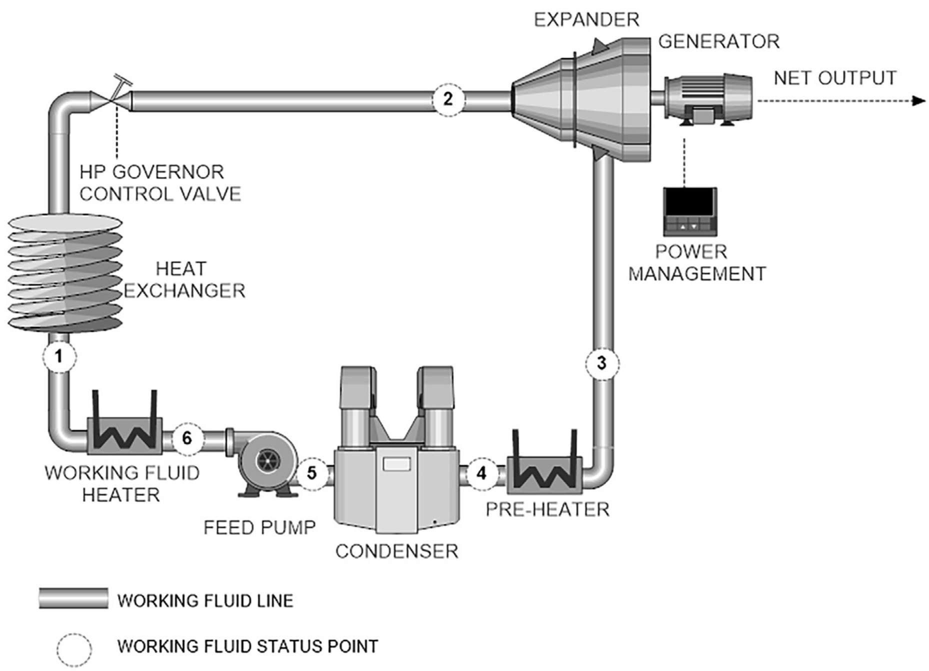

Fig. 1. Schematic diagram of an ORC system.

the pump and the pressurized fluid is ready to start the cycle again. The input power of the isentropic compression in a pump is given as Eq. (6), [23].

$$W_p = \dot{m}_{wf} \times (h_6 - h_5) \tag{6}$$

The recovered heat, preheat the working fluid to pint 1 and the cycle is repeated.

$$h_1 = \eta_{rec} \times (h_3 - h_4) + h_6 \tag{7}$$

The net output power of the cycle is, [23]:

$$W_{net} = W_{ex} - W_p \tag{8}$$

The thermal efficiency can be calculated as:

$$\eta_{th} = \frac{W_{net}}{Q} \tag{9}$$

3.2. Working fluid aging model

The working fluid thermal stability is the capability to preserve unchanged all its main physical properties because of the heating. As a general rule, the greater the thermal stability, the greater maximum temperature at which the fluid can be used [24].

The thermal degradation of a working fluid occurs when the temperature breaks the molecular bonds, thereby forming new compounds. For example, among the products of thermal decomposition of toluene at about 340 (°C), there are Hydrogen, methane, C_2, and C_3 alkanes and alkenes (in the gaseous phase). As the degradation of a working fluid increases exponentially with the temperature, an increase of 10 (°C) in the bulk temperature can double the rate of decomposition, halving the operating life of the fluid [24].

The rate of conversion of the moles, in the gaseous phase, is given by [18]

$$\frac{dn}{dt} = -Kn \tag{10}$$

$$K = A\exp(B/T) \tag{11}$$

The variable n is the number of mole of the substance at time t, $dn/dt = v$ is the velocity reaction, and K is said to be the rate constant of the reaction. Assuming $\alpha = \Delta n/n$ as the degree of dissociation over time Δt, the integration over time of Eq. (11) gives, [18]:

$$\frac{\ln(1-\alpha)}{\Delta t} = -K \tag{12}$$

The velocity reaction increases exponentially with the test temperature. The K factor for toluene is formulated as follows [18]

$$K \times 10^9 = 4114.7 \times \exp(-4711/T) \tag{13}$$

Similarly, the velocity factor for Cyclopentane can be evaluated by Eq. (14) [18].

$$K \times 10^{-2} = \exp(-15742/T) \tag{14}$$

3.3. Economic evaluation

The capital investment cost of power plant equipment consists of two main parts. A direct cost reflecting the materials and labor required for the installation, the electrical equipment, the controls and instrumentation, and an indirect cost that cover the personnel salary and transportation costs for shipping equipment to the plant site. The capital investment cost can be calculated as Eq. (16).

$$C_{CI} = C_P^0 \times F_1 \tag{16}$$

where C_P^0 is the capital cost of equipment in base condition, and $F_1$is the base module factor. The capital cost of equipment in base condition is calculated as Eq. (16).

$$\log_{10} C_P^0 = A_1 + A_2 \times \log_{10} AA + A_3(\log_{10} AA)^2 \tag{17}$$

The capital cost of the generator in base condition can be calculated as Eq. (17).

$$C_{P,gen}^0 = 690(W_{net})^{0.95} \tag{18}$$

And, the base module factor is derived from Eq. (18).

$$F_1 = B_1 + B_2 \times F_2 \times F_3 \tag{19}$$

$$\log_{10} F_3 = C_1 + C_2 \times \log_{10} P + C_3(\log_{10} P)^2 \tag{20}$$

P is the operating pressure, and the constant parameters of Eqs. (15)–(19), for the ORC equipment is described in [25,26] and presented

Table 1
Coefficients of ORC equipment for cost calculations.

Equipment	A_1	A_2	A_3	B_1	B_2	C_1	C_2	C_3	F_1	F_2	AA
Expander	2.2476	1.4965	−0.1618	–	–	–	–	–	6.1	–	kW
Pump	3.3892	0.0536	0.1538	1.89	1.35	−0.393	0.3957	−0.0022	–	1.5	kW
Heat exchanger	4.3247	−0.0303	0.1634	1.63	1.66	0.0388	−0.1127	0.0818	–	1	m^2
Generator	–	–	–	–	–	–	–	–	1.5	–	kW

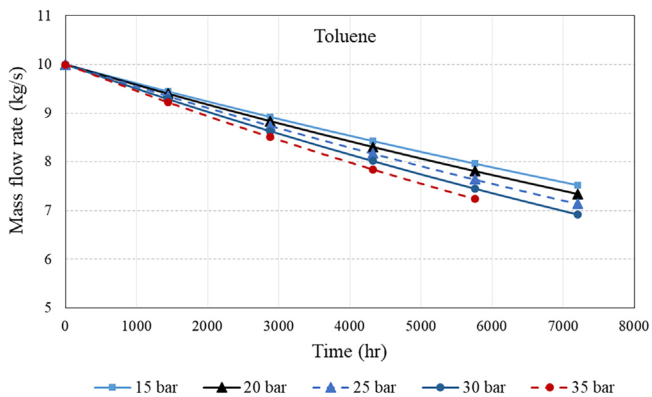

Fig. 2. Working fluid mass flow rate variation during the plant lifetime.

in Table 1.

The operation and maintenance (O&M) costs of the ORC power plant includes a fixed cost and an operating cost.

$$C_{O\&M} = C_{fix} + C_{oper} \tag{21}$$

The fixed O&M cost includes the annual cost of property taxes and liability insurance and calculated as Eq. (22).

$$C_{fix} = 0.02 \times C_{CI} \tag{22}$$

The operating O&M cost covers annual maintenance equipment cost.

$$C_{oper} = 0.0805 \times C_{CI} \tag{23}$$

3.4. Aging based optimal design and operation scheduling

In order to find the optimal working fluid and operation schedule, an optimization model is developed. The proposed optimization model has three main components including an objective function, a collection of decision variables, and constraints. The objective function is defined based on the operational strategy of the power plant. Mostly, the profit maximization is the operational strategy of the power plants that can be calculated as Eq. (24).

$$profit = \int_0^t W_{net} \times C_p.\, dt \tag{24}$$

The solution to the optimization problem is the set of values of the decision variables for which the objective function reaches its optimal value. The decision variables in this study are working fluid type, power plant capacity, and operating conditions including maintenance intervals.

Finally, a collection of constraints that restricts the values of the decision variables exists. These constraints include ORC thermodynamic model (Eqs. (1)–(9)), working fluid aging model (Eqs. (10)–(14)), and economical and technical constraints.

4. Results and discussion

The proposed model is employed to determine the optimal working fluid and operation schedule of an ORC system operating on the exhaust heat from a gas turbine. The considered gas turbine in this work is the GE10-1 model of GE products. The exhaust heat of gas turbine is recovered in a heat exchanger to evaporate/superheat the fluid in an ORC system. The flow diagram of the system is presented in Fig. 1. In addition, the main characteristics of the studied ORC system are presented in Table 1 and more details of the system are provided in Ref. [4].

4.1. Performance deterioration

As explained in the previous section, the working fluid degrades during the life time of the ORC systems. Therefore, the mass flow rate of cycle declines as the operation time increases. Toluene and cyclopentane showed high global efficiency in a gas turbine combined cycle and a low purchase cost of the fluid. Carcasci et al. [4] analyzed toluene and cyclopentane and concluded these working fluids are a good solution to replace steam in small sized combined cycles. Moreover, Toluene and cyclopentane are recognized as a really thermally stable working fluid [18]. Studying and investigating the effects of fluid degradation rate on the ORC system, the toluene and cyclopentane are considered as two working fluids. Also, the cycle's operation and efficiency of toluene and cyclopentane are evaluated and the results are compared. The mass flow rate of the cycle at the start point for both of them is deemed to be 10 (kg/s). Also, it is considered that toluene leaves the HRSG at saturation temperature, while cyclopentane operates slightly superheated (15 (°C) above saturation temperature).

The mass flow rate variation of the toluene as working fluid during the operation lifetime for different pressures is depicted in Fig. 2. It is clear that toluene degradation has a significant effect on the cycle's mass flow rate. As shown, $\dot{m}_f$ decreases dramatically by the growth of system's life. For instance, the flow rate has about 15% reduction in the first 4000 h of operation ($P_h = 15\,bar$). Also, the fluid decomposition increases remarkably by the increment of high pressure of the cycle (P_h). The mass flow rate decreases to 8.2 (kg/s) for $P_h = 15$ (bar) at the first 5000 h, while this value is equal to 7.5 (kg/s) for $P_h = 35$ (bar) which indicates 0.7 (kg/s) reduction of flow.

It is clear that saturation pressure and temperature are dependent (the higher pressure, the higher temperature). So, the outlet temperature of toluene from HRSG increases by the increment of the pressure. Moreover, the decomposition rate of fluid changes exponentially with temperature (Eqs. (13) and (14)). Therefore, the rate of degradation would be much higher for high pressure in comparison with low pressure. This is why the cycle's mass flow rate at $P_h = 35$ (bar) is about 10% lower than that of the $P_h = 15$ (bar).

The variations of the cyclopentane flow rate as working fluid for different values of the inlet expander pressure are demonstrated distinctively in Fig. 3. The increment of the operating hours of system changes significantly the degradation rate and mass flow rate. As shown, by increasing the operation time up to 12,000 (h), $\dot{m}_f$ declines from 10 (kg/s) to 6.8 (kg/s) ($P_h = 25\,bar$).

Fig. 4 represents the power production of cycle variations versus the operation time of system for toluene. It can be seen that for a certain value of the high pressure, the amount of the produced power decreases considerably by escalating the lifetime. According to Eq. (3), the mass flow rate has a direct effect on the power production. As illustrated above, cycle's mass flow rate has downward trend during the system operation which reduces the power production.

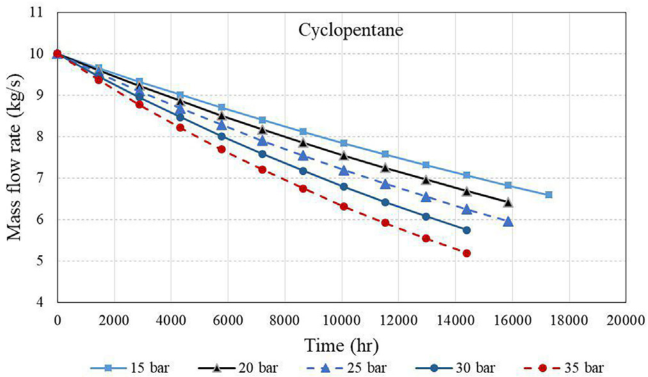

Fig. 3. Variation of the cyclopentane flow rate over the cycle lifetime.

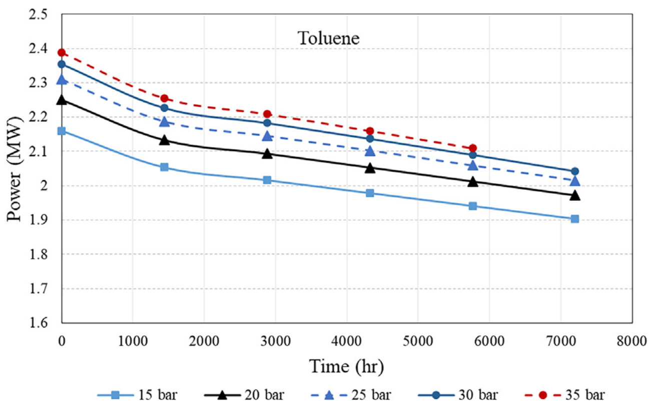

Fig. 4. Output power deterioration through operation time for Toluene.

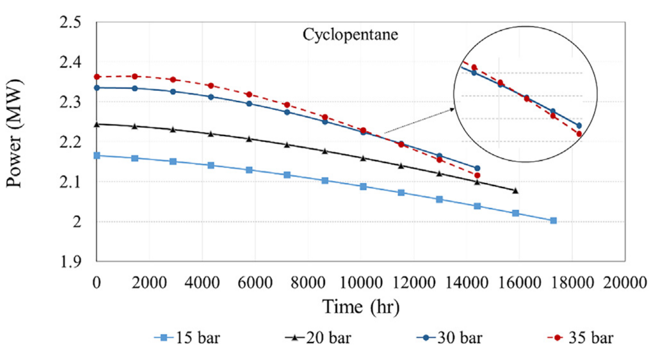

Fig. 5. Cyclopentane power production variation operating hours of the system.

Fig. 5 reveals the values of produced power versus different inlet pressures of the expander for operation hours of 0 (hr) to 20,000 (hr). Similarly, the output power of cyclopentane declines over the cycle's lifetime. The point about the cyclopentane is that the rate of degradation is much higher at higher pressures than that one for low pressures. So, the mass flow rate at higher pressures in comparison with lower ones decreases sharply resulting in rapid reduction of produced power during system's life. As depicted, the cyclopentane power production curve for $P_h = 35$ (bar) has a steep reduction by increasing the time. In such a way that after reaching a specific point ($t = 11000$ (hr)), the power generation for this pressure would be less than output power for $P_h = 30$ (bar).

4.2. Optimal design

The net power production at the start point versus different pressures for toluene and cyclopentane is compared in Fig. 6. The results show that for all pressures, at the beginning time, the produced power

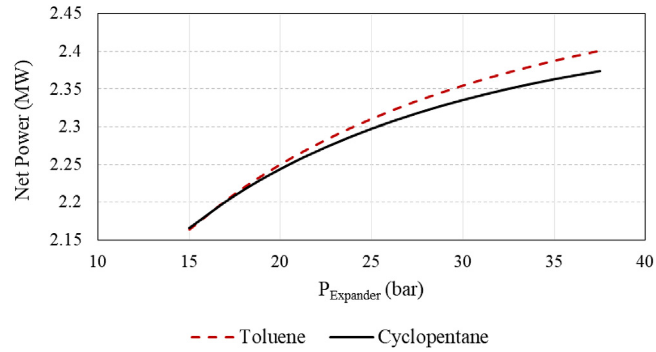

Fig. 6. Net power production comparison for toluene and cyclopentane at the beginning time.

of toluene as a working fluid is equal or much higher than that of the cyclopentane. In many studies, such as Ref. [4], the start point power production is considered as a decisive point for the selection of working fluid. Therefore, in this view point, the toluene would operate better and its performance is much higher in comparison with cyclopentane. Therefore, the toluene should be selected as working fluid of the ORC system. However, there is a major oversight in this method of working fluids selection that the fluid decomposition is not considered. While performance deterioration through the time is an important issue in evaluating the ORC systems operation.

Fig. 7 shows the net power production of the plant for toluene and

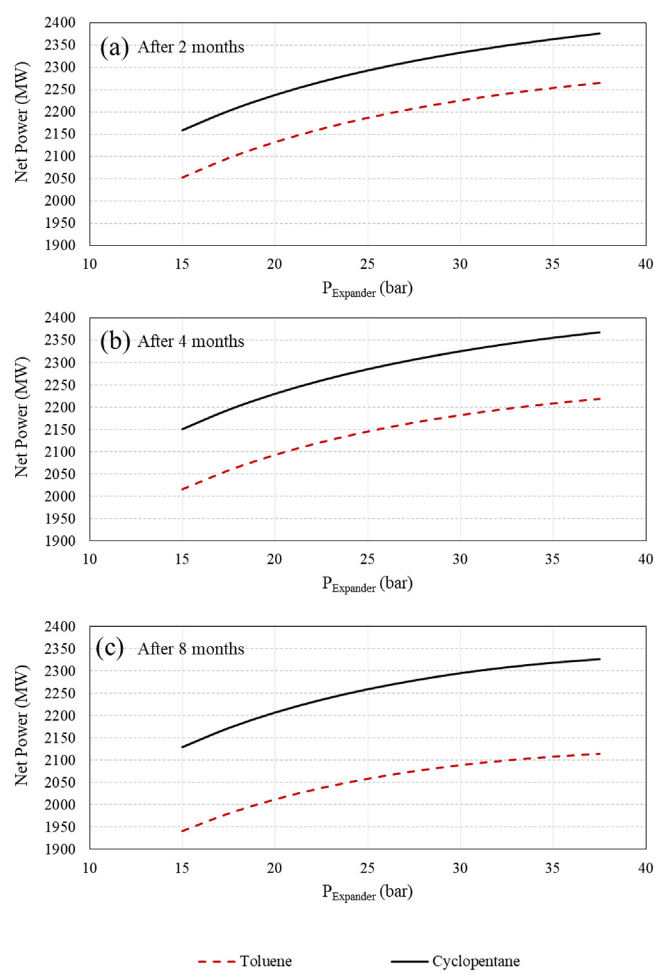

Fig. 7. Net power production for toluene and cyclopentane over different operation times.

cyclopentane for different time periods. After two months of operation, power production of the toluene reduces and the curve of power generation for toluene would be located below the cyclopentane, for all values of pressure.

In comparison with cyclopentane, the degradation rate of toluene would have higher values by the increment of time and this difference increases during the system's operation. As shown, the difference of the power production for toluene and cyclopentane in six months is much higher than two months. So that, after eight months, the distance between curves increases and power production of cyclopentane on average is about 11% higher than toluene. These results reveal that selection of working fluid just on the basis of the start point power production is not reliable. In this study, toluene would be selected if the beginning time power production was the basis of the decision while system's long-term evaluation determined that cyclopentane is the correct choice.

Therefore, it is necessary to consider the fluid degradation to select the working fluid and design the ORC systems. Also, the simulation and optimization of the system should be evaluated through long-term operation.

4.3. Optimal operation schedule

In order to find the optimum maintenance and operation schedule, the cost of reduced work as a result of the fluid decomposition is compared with the maintenance cost. The working fluid refilling cost is considered to be about 140 k$ [27]. Therefore, the cost of power deterioration due to the fluid degradation is evaluated and system operation continues until the cost of the lost work be less than the refilling cost. Fig. 8. Shows the power loss price of toluene over time for different pressure values.

The optimized maintenance intervals of the toluene and cyclopentane for different values of the operating pressures are illustrated in Fig. 9. As it is shown, the maintenance intervals for cyclopentane is much higher than that of the toluene for all values of expander pressures. The higher the rate of decomposition of toluene compared to cyclopentane is the reason for this difference.

In addition to the economical limit (power deterioration cost versus refilling cost), an essential technical constraint should be taken to account which is the maximum functional temperature for working fluids of Rankin cycles [24]. The maximum operative temperature for toluene and cyclopentane is about 300 °C. As described in last sections, the cycle's mass flow rate decreases over operation lifetime which rises the maximum temperature of the cycle. So, it is necessary to obtain the maintenance intervals in such a way that avoid the maximum working fluid temperature.

The main difference between the economic and technical constraints is that for economical limit the operation of the cycle continue until the cost of lost work be less than the refilling cost, while for the technical limit, the cycle operation will terminate when the maximum operating temperature reaches the technical limit.

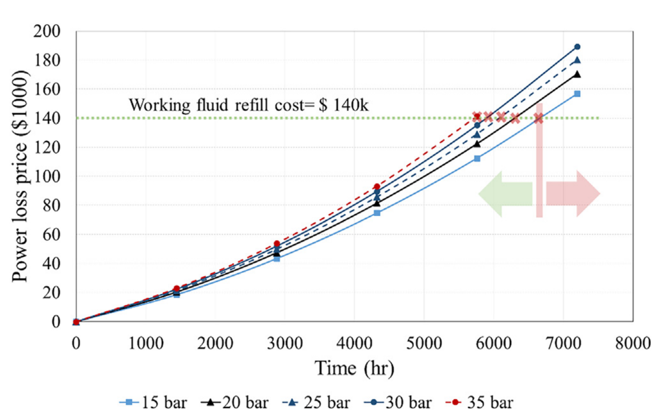

Fig. 8. Power loss price of toluene over time for different pressure values.

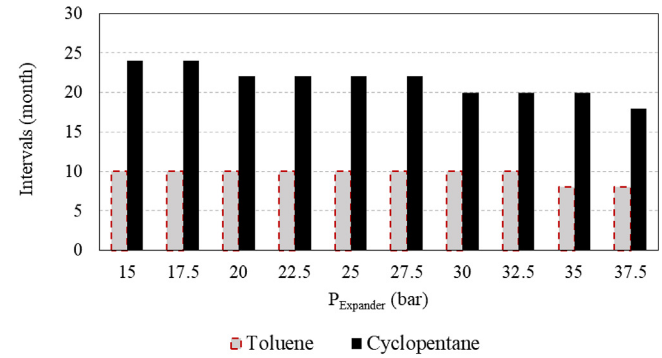

Fig. 9. Maintenance intervals of the ORC system for toluene and cyclopentane at different expander pressures considering the economical limit.

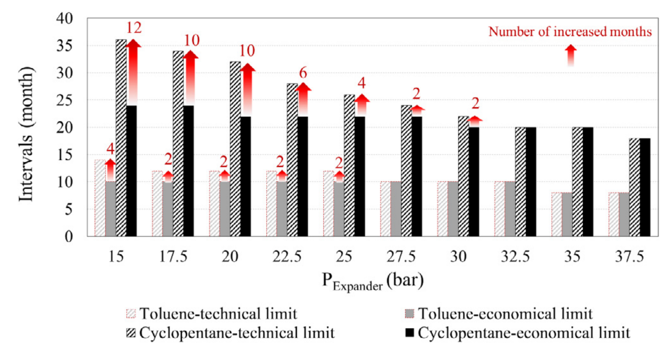

Fig. 10. Maintenance intervals of the ORC system for toluene and cyclopentane at different expander pressures considering the technical limit.

Optimization of the ORC system with two different constraints (economical and technical) are done and comparison between economical and technical limits are depicted in Fig. 10. The results indicate that optimum maintenance intervals are changed and technical limit results in a major increment of the refilling intervals, almost for all the pressures. According to the results, replacing the economical constraint with technical limit declines the operating cost and is preferable and beneficial. But, power deterioration cost due to longer operation time and higher fluid degradation is not considered. Comparison between the monthly profit of ORC system considering economical and technical limits for toluene and cyclopentane is outlined in Fig. 11. As can be seen, the economical limit results in more or equal benefit while it satisfies the technical constraint. So, using economical limit is more reliable and recommended.

4.4. Economic analysis

Fig. 12 shows the total operating cost of the ORC system for toluene and cyclopentane during five years of operation as a function of pressure. The cost of operation for both of the working fluids is approximately the same. But, the refilling cost of toluene is much higher than cyclopentane which this difference increases by rising the expander inlet pressure. Therefore, selecting the cyclopentane as working fluid is more economical and recommended.

Comparing two working fluids (toluene and cyclopentane) and analyzing the system profit, the cost of electricity for different values of operating pressure is evaluated and represented in Fig. 13. According to this figure, there is a considerable difference in the cost of electricity between toluene and cyclopentane. The cost of electricity generation for toluene is about 0.03 ($/kW.hr) more than cyclopentane, indicating that the cost of electricity with this fluid is about 30% higher. So, using cyclopentane will be more economical.

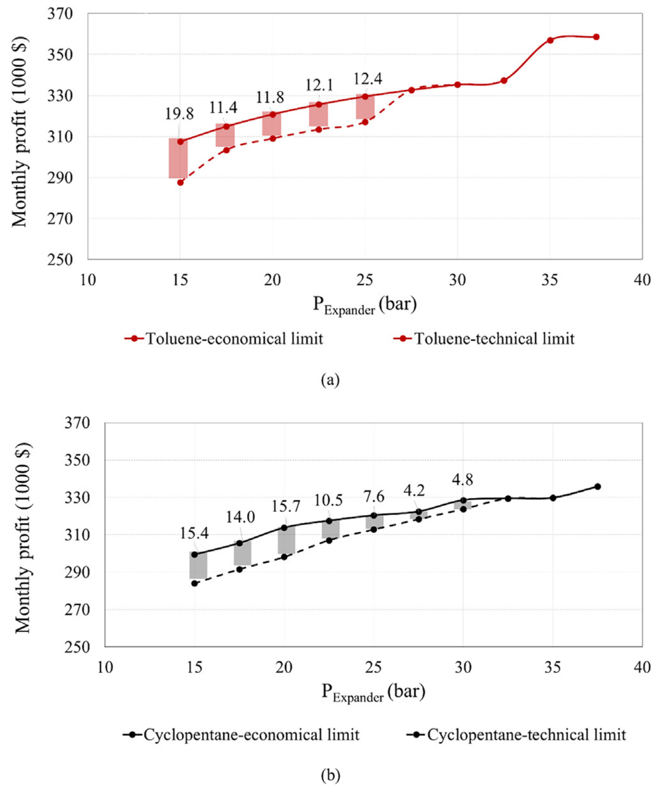

Fig. 11. Comparison between the monthly profit of ORC system considering economical and technical limits, (a): Toluene, (b): Cyclopentane.

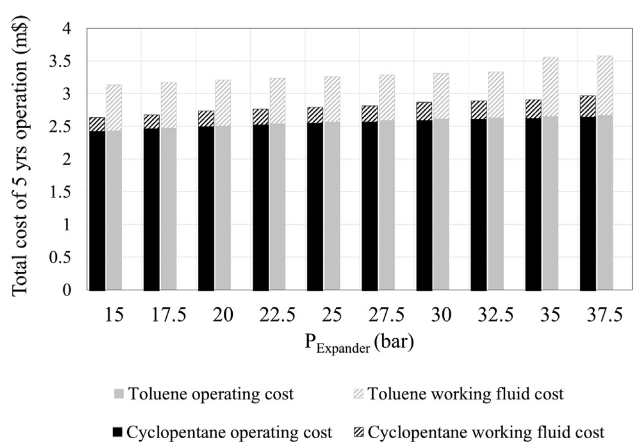

Fig. 12. Total 5 yrs. operating cost of the ORC system for toluene and cyclopentane at different expander pressures.

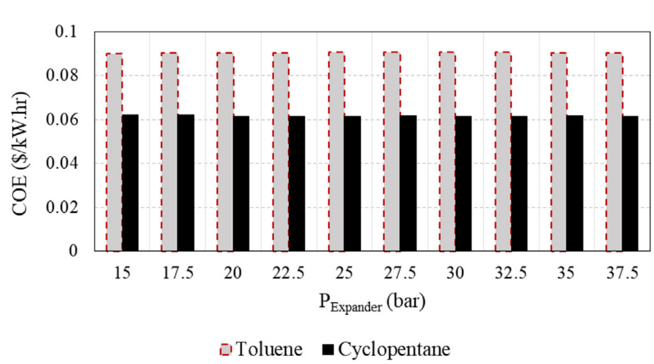

Fig. 13. Cost of electricity at different expander pressure.

5. Conclusions

An Organic Rankine Cycle can be a good solution for heat recovery from gas turbine cycle. System working fluid, capacity and operating conditions are the main parameters that affect the economics of ORC plant long-term operation. In addition, in ORC plants, working fluid decomposition is dramatic in long-term operation and deteriorates system performance. Newly generated substances could have the ability to produce electricity or aggravate former performance, depending on substance characteristics. Therefore, the thermal degradation of working fluid affect system optimal working fluid selection, design and operation. In this study, the effect of working fluid decomposition is considered in the optimization procedure including working fluid selection, and system capacity and operation optimization.

Working fluid decomposition depends on the fluid type, temperature and time that is analyzed quantitatively and its impact on the ORC optimal capacity and operating conditions for toluene and cyclopentane are pointed out. Considering degradation rate of working fluids, optimizing the operation schedule and maintenance intervals, the following conclusions can be drawn:

- The mass flow rate of cycle decreases dramatically by the growth of system's life.
- The fluid decomposition increases remarkably by the increment of high pressure of cycle.
- The produced power decreases considerably by escalating the lifetime.
- Although, at the start point, the produced power of toluene is equal or much higher than cyclopentane. But, after eight months, power production of cyclopentane on average is about 11% higher than toluene.
- Optimization of the ORC system with two different constraints (economical and technical) shows that using economical limit is more reliable and recommended.
- The maintenance intervals for cyclopentane is much higher than that of the toluene for all values of expander pressures.

The results indicated that using the toluene as a working fluid increases the degradation rate and cost of maintenance and electricity generation. Therefore, toluene is not the right fluid choice for this plant configuration and using cyclopentane will be more economical in long-term operation.

In sum, this study reveals that selection of working fluid just on the basis of start point power production is not reliable. Therefore, it is necessary to consider the fluid degradation to select the working fluid and design the ORC systems. Also, the simulation and optimization of the system should be evaluated through the long-term operation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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